

Materials Selection in Mechanical Design

Sixth Edition

Metals	Density	Modulus	Strength	Fr. toughness	Sp. heat	T-conduction	T-expansion
Cast iron	7,100	170	390	35	460	46	11
Carbon steel	7,800	210	630	50	480	50	12
Low alloy steel	7,800	210	870	56	480	43	12
Stainless steel	7,700	200	540	88	480	19	13
Al-alloys	2,800	72	350	10	900	160	24
Cu-alloys	8,300	100	170			120	19
Mg-alloys	1,800	44	120			79	26
Pb-alloys	11,000	15	25			28	28
Ni-alloys	8,400	210	410			85	13
Ti-alloys	4,600	110	870			11	9
Zn-alloys	6,600	83	160			120	27
Ceramics							
Alumina	3,700	370	370			37	7.2
Silicon carbide	3,200	420	505			105	4.4
W-carbide	19,000		430			70	6.1
Zirconia	6,100		450			24	11.0
Glasses							
Soda glass	2,500					1.9	9.3
Pyrex	2,200					1.2	3.6
Polymers							
ABS	1,000					0.26	95
PA	1,100					0.24	130
PE					1,800	0.42	160
PP					1,900	0.14	150
PET	1,300				1,200	0.14	120
PLA	1,300				1,200	0.14	140
PS	1,000			0.9	1,200	0.13	120
PVC	1,400			3.7	1,000	0.18	73
Epoxies	1,200			0.6	1,200	0.19	97
Phenolics	1,300			1.0	1,500	0.15	120
Polyester	1,200			1.4	1,500	0.29	130
Composites							
GFRP	1,900			13	1,100	0.47	17
CFRP	1,500			11	970	1.80	2

Michael F. Ashby



Physical constants in SI units

Physical constant	Value in SI units	
Absolute zero temperature	-273.2	°C
Acceleration due to gravity, g	9.807	m/s ²
Avogadro's number, N_A	6.022 x 10 ²³	-
Base of natural logarithms, e	2.718	-
Boltzmann's constant, k	1.381 x 10 ⁻²³	J/K
Faraday's constant K	9.648 x 10 ⁴	C/mol
Gas constant, $\bar{R}$	8.314	J/mol/K
Permeability of vacuum, μ_o	1.257 x 10 ⁻⁶	H/m
Permittivity of vacuum, ϵ_o	8.854 x 10 ⁻¹²	F/m
Planck's constant, h	6.626 x 10 ⁻³⁴	J/s
Velocity of light in vacuum, c	2.998 x 10 ⁸	m/s
Volume of perfect gas at STP	22.41 x 10 ⁻³	m ³ /mol

Conversion of units, general

Quantity	Imperial unit	SI unit
Angle, θ	1 rad	57.30°
Density, ρ	1 lb/ft ³	16.03 kg/m ³
Diffusion coefficient, D	1 cm ² /s	1.0 x 10 ⁻⁴ m ² /s
Energy, U	See inside back cover	
Force, F	1 kgf	9.807 N
	1 lbf	4.448 N
	1 dyne	1.0 x 10 ⁻⁵ N
Length, ℓ	1 ft	304.8 mm
	1 inch	25.40 mm
	1 Å	0.1 nm
Mass, M	1 tonne	1000 kg
	1 short ton	908 kg
	1 long ton	1107 kg
	1 lb mass	0.454 kg
Power, P	See inside back cover	
Stress, σ	See inside back cover	
Specific heat, C_p	1 cal/gal.°C	4.188 kJ/kg.°C
	Btu/lb.°F	4.187 kg/kg.°C
Stress intensity, K_{Ic}	1 ksi √in	1.10 MN/m ^{3/2}
Surface energy, γ	1 erg/cm ²	1 mJ/m ²
Temperature, T	1°F	0.556°K
Thermal conductivity, λ	1 cal/s.cm.°C	418.8 W/m.°C
	1 Btu/h.ft.°F	1.731 W/m.°C
Volume, V	1 Imperial gall	4.546 x 10 ⁻³ m ³
	1 US gall	3.785 x 10 ⁻³ m ³
Viscosity, η	1 poise	0.1 N.s/m ²
	1 lb ft.s	0.1517 N.s/m ²

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Sixth Edition

Michael F. Ashby



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Butterworth-Heinemann is an imprint of Elsevier



Butterworth-Heinemann is an imprint of Elsevier
125 London Wall, London EC2Y 5AS, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

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ISBN: 978-0-443-16028-8

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Publisher: Peter Linsley
Acquisitions Editor: Stephen Merken
Editorial Project Manager: Aleksandra Packowska
Production Project Manager: Haritha Dharmarajan
Cover Designer: Matthew Limbert

Typeset by MPS Limited, Chennai, India



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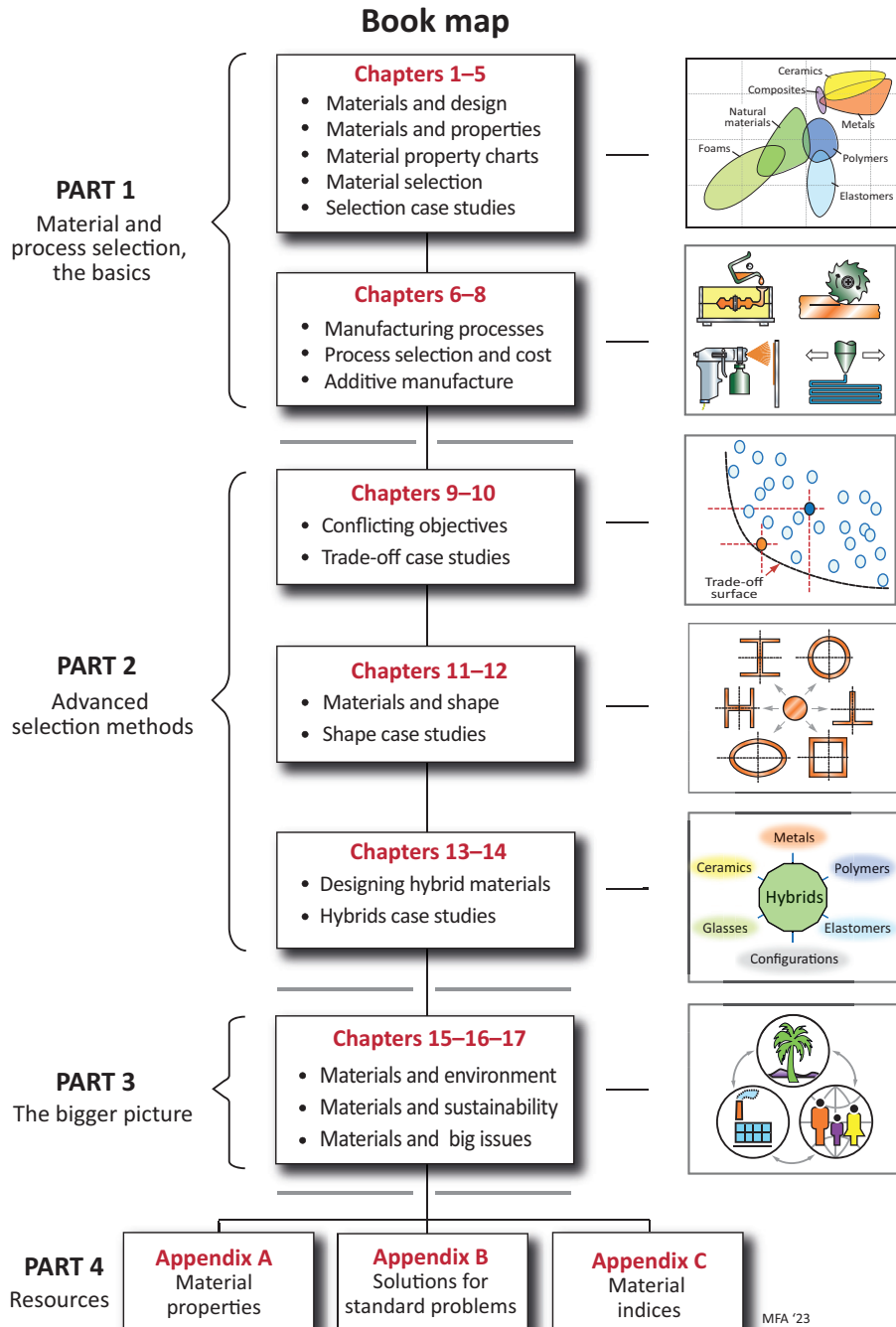
Preface and Acknowledgements

This book is about materials and processes, how to choose them, and how changing conditions in the world influence the priorities of the choice. It has four parts, mapped out in [Fig. P1](#).

Part 1 is a basic guide to materials and process selection. The material/process landscape is broad—there are a great number of options. To navigate it, you need maps. Material and process property charts provide them. A map alone is not enough. Finding a route needs a compass and a guide. Design requirements—the list of “must-haves” for a material in a given design—point to the direction; material indices act as guides along the route. And once a material is chosen, manufacturing processes are needed to shape, join, and finish it. Methods for doing all this are developed in Part 1. Travelers have crossed this terrain before. Some of their experience is condensed in the Case Studies that appear throughout the book.

Part 2 takes the exploration into more challenging territory, extending the methods of Part 1. Design requirements can be demanding, requiring several, often conflicting, criteria to be met at the same time: “The component must be light, *and* cheap *and* environmentally sound,” for example. The tools of Part 1 can handle any one of these, but not all three at once. Trade-off methods allow a compromise to be reached that best meets them all. And there’s more. Design requirements don’t specify a *material*; they specify a *function*: “support bending loads” or “insulate against cold,” for instance. Solid materials can support loads and insulate, but the job is done more efficiently by first shaping the material into a tube or a foam. And the best choice of material, sometimes, is not just one, but a hybrid made by combining more than one. Part 2 provides tools to negotiate this tougher terrain.

Part 3 introduces the changing context in which materials are chosen and used. The world is not static. The climate is changing. The global population is increasing and their affluence is increasing faster. So, too, is their consumption of almost everything. Their needs deprive other species (not just mammals) of the space and surroundings they need to survive. And their leftovers, their

**FIG. P1**

The structure of the book.

“waste,” is becoming an acute problem. Adapting the ways in which we use and conserve materials, and the social and economic constraints that limit how we do it, comes under the broad heading of sustainability. Part 3 takes a drone’s-eye view of this more global landscape.

Part 4, the final part, is for reference. It contains a set of resources: data for engineering materials, useful solutions for standard problems, and a catalog of material indices. They are used in the examples, case studies, and exercises that appear throughout the book.

How does this sixth edition differ from the fifth? The text and figures have been extensively revised. There are new chapters on Additive manufacture, Materials and sustainable development, and Big issues and materials. There are more examples and exercises, placed at the ends of the relevant chapters. Material efficiency, criticality, circularity, and sustainability are introduced. Appendix A, material property data, is updated using the most reliable available sources.

This book interfaces with a set of others, all of which use the same underlying way of thinking. At the more elementary level, the text *Materials, Engineering, Science, Processing and Design*¹ introduces materials from an engineering perspective; it is aimed at first-year undergraduates. At the more advanced levels, the texts *Materials and the Environment*,² *Materials and Sustainable Development*,³ and *Materials and Design*⁴ enlarge on the eco/sustainability aspects that appear in the last three chapters of this book.

Many of the procedures developed here are implemented in the Ansys Granta EduPack⁵ Materials and Process Selection software, which, if available, forms a helpful adjunct to the text but is not necessary for its adoption.

HOW TO USE THIS BOOK

It’s not a book to sit down and read cover-to-cover. You may not need it all. To find your way, you need a map with friendly instructions—think of it as

¹ Ashby, M. Shercliff, H. and Cebon, D. (2023) *Introduction to Materials Science and Engineering—a Design-led approach*. Butterworth-Heinemann, Oxford, ISBN: 9780081023990.

² Ashby, M.F. (2021) *Materials and the Environment—eco-informed material choice* 3rd edition, Butterworth Heinemann, Oxford. ISBN 978012821521.

³ Ashby M.F. (2023) *Materials and Sustainable Development*, 2nd edition, Butterworth-Heinemann Ltd, Oxford. ISBN- 978-0-323-98361-7.

⁴ Ashby, M.F. and Johnson K. (2014) *Materials and design—the art and science of materials selection in product design*, 3rd edition, Butterworth Heinemann, Oxford, UK. ISBN 978-0-08-098205-2.

⁵ The CES EduPack materials and process selection platform, is a product Ansys Granta, <https://www.ansys.com/en-gb/products/materials/granta-edupack>.

a lonely planet guide to materials and process selection. There's no point in spending time reading about places you don't want to go to. Part 1 can stand on its own as a basic introduction to systematic materials and process selection. Adding Part 2 extends the range, allowing selection to meet a more complex set of design requirements. Part 3 provokes discussion of the underlying forces that are changing the way we select and use materials now and into the future. It can be read on its own or used to provide the wider context in which material selection takes place.

Like any other book, the contents of this one are protected by copyright. Generally, it is an infringement to copy and distribute materials from a copyrighted source. But the best way to use the charts that are a feature of the book is to have a clean copy on which you can draw, try out alternative selection criteria, write comments, and annotate; many of the exercises require it. Although the book itself is copyrighted, the instructor or reader is authorized to make unlimited copies of the charts and to reproduce these for teaching purposes, provided that the source is referenced.

Mike Ashby
Cambridge, December 2023

ACKNOWLEDGMENTS

Many colleagues have been generous with ideas and constructive suggestions. I particularly wish to thank Professor David Cebon, Professor Norman Fleck, Professor Ken Wallace, Professor John Clarkson, Professor Julian Allwood, Dr. John Cullen and Dr. Hugh Shercliff of the Engineering Department, Cambridge University; Professor Yves Bréchet of the University of Grenoble; Professor Anthony Evans of the University of California at Santa Barbara; Professor John Hutchinson of Harvard University; Dr. Amal Esawi of the American University in Cairo, Egypt; Dr. Ulrike Wegst of the Thayer School of Engineering at Dartmouth; Professor Paul Weaver of the Department of Aeronautical Engineering at the University of Bristol; and Professor Michael Brown of the Cavendish Laboratory, Cambridge, UK. Equally valuable has been the contribution of Dr. Patrick Coulter and my many colleagues at Granta Design, Cambridge (now Ansys Granta).

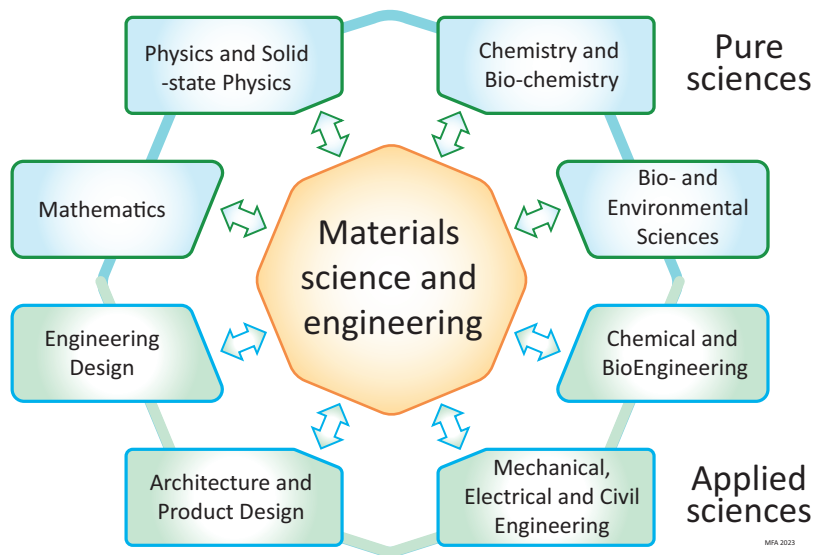


PART

Materials and Process Selection: The Basics

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Introduction: Materials and Design



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1.1 INTRODUCTION AND SYNOPSIS

“Design” is one of those words that can mean all things to all people. Every manufactured thing, from the most lyrical of ladies’ hats to the greasiest of gearboxes, qualifies, in some sense or other, as a design. It can mean yet more. Nature, to some, is Divine Design; to others it is design by Natural Selection. The reader will agree that it is necessary to narrow the field, at least a little.

This book is about the role of materials in engineering design. The components that make up a product have shape; they have mass; they carry loads; they conduct heat and electricity; they are exposed to wear and to corrosive environments; they are made of one or more materials; and they must be manufactured. The book describes how these are related.

Materials had limited design since man first made clothes, built shelters, and waged wars. Today the range of materials and processes to shape them is expanding rapidly. This expansion creates new opportunities, but it also brings problems. We now use more materials in greater quantities than ever before, and we use them in ways that—at present—are wasteful. The book develops strategies for seizing the opportunities and tackling the problems in ways that are sustainable.

1.2 MATERIALS IN DESIGN

The number of materials available to engineers is very great: 200,000 or more. Although standardization aims to reduce the number, the continuing appearance of new materials with novel, exploitable properties expands the options further. How, then, do engineers choose, from this vast menu, the material best suited to their purpose? Rely on experience? That's how it was done in the past, passing on this experience to apprentices who, later in their lives, might themselves assume the role of the in-house materials expert.

There is no question of the value of experience. But many things have changed in the world of engineering, and all of them work against the success of simple reliance on past practice. There is the drawn-out time scale of apprentice-based learning. There is job mobility, meaning that the expert who is here today may be gone tomorrow. And there is the rapid evolution of materials information, already mentioned. A strategy relying on experience is not in tune with the fast-moving digital environment in which design takes place today. We need a *systematic* procedure—one with steps that can be taught quickly, is robust in the decisions it reaches, allows computer implementation, and is compatible with modern design methods.

Design is the process of translating an idea into detailed information from which a product can be manufactured. Each of its stages requires decisions about the materials of which the product is to be made and the processes for shaping and joining them. Cost enters, both in the choice of material and in the way the material is processed. Materials are derived from natural resources—ores for metals, oil for polymers, and minerals for ceramics and glasses. Many of these resources are finite, and all, in conversion to useful materials, need energy. Materials efficiency has now become as important as energy efficiency, with efforts increasingly directed towards a circular materials economy, one that re-uses as much as possible, minimizing the draw-down from the natural resource base. And it must be recognized that good engineering design alone is not enough to sell products. In almost everything from home appliances to automobiles and aircraft, the form, texture, feel, color, beauty, and meaning of the product—the satisfaction it gives the person who owns or uses it—are important. This aspect, known confusingly as *industrial design*, is one that, if

neglected, can lose markets. Good design works; excellent design also gives pleasure.

Design challenges, almost always, are open ended. They do not have a unique “correct” solution, though some solutions will clearly be better than others. They differ from the analytical problems used in teaching mechanics, structures, or thermodynamics, which generally do have single, correct answers. So the first tool a designer needs is an open mind: the willingness to consider all possibilities. But a net cast widely draws in many different fish. A procedure is necessary for selecting the excellent from the merely good.

Our aim is to develop a methodology for selecting materials and processes that is *design led*; that is, it uses, as inputs, the functional requirements of the design (Fig. 1.1). To do so we must first look briefly at the design process itself. Like most technical fields it is encrusted with its own special jargon, some of it bordering on the incomprehensible. We don’t need much, but we can’t avoid it altogether. The next section introduces some of the words and phrases—the vocabulary—of design, the stages in its implementation, and the ways in which materials selection links with these.

1.3 THE DESIGN PROCESS

The starting point of a design is a *market need*; the end point is the full *specification* of a solution that fills the need. It is essential to define the need precisely, that is, to formulate a *need statement* expressed as a set of *design requirements*. Writers on design emphasize that the need statement should be solution neutral (that is, it should not imply how the need will be met), to avoid narrow thinking channeled by pre-conceptions. Between the need statement and the

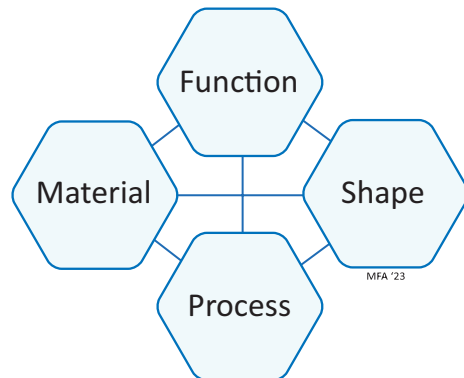
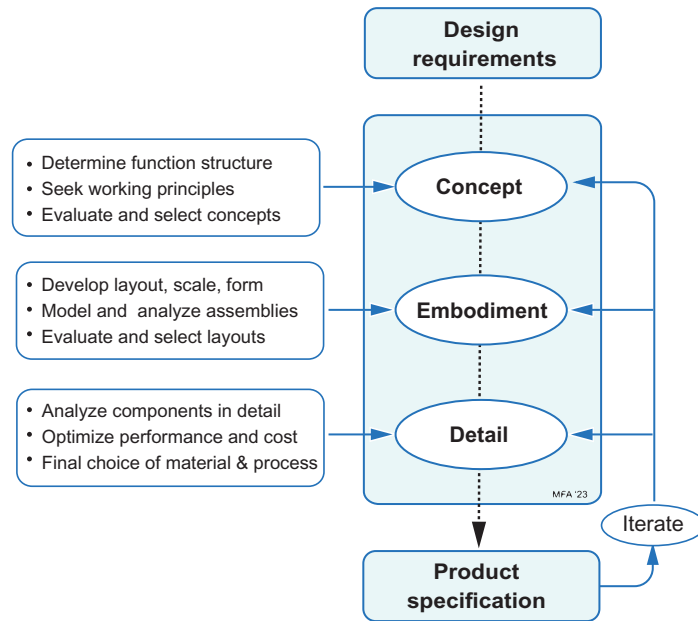


FIGURE 1.1

The central problem of materials: the interaction between function, material, process, and shape.

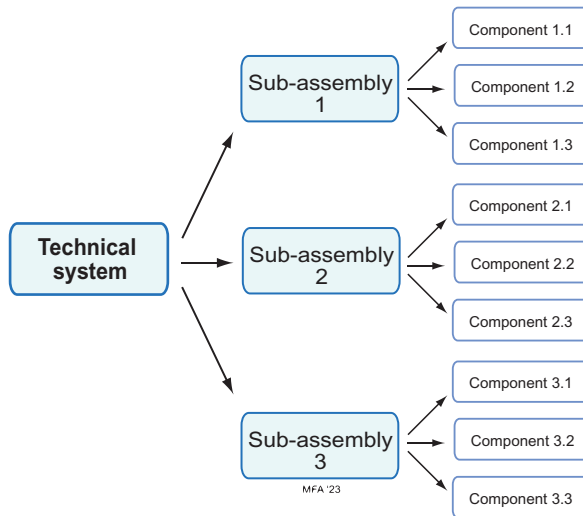
**FIGURE 1.2**

The design flow chart.

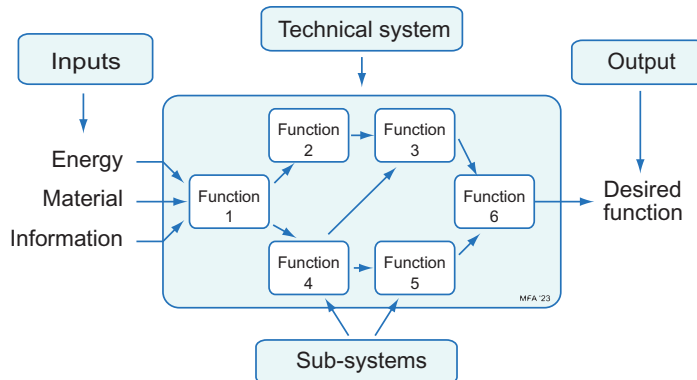
product specification lie the stages shown in Fig. 1.2: *concept*, *embodiment*, and *detailed design*, explained in a moment.

The product itself is called a *technical system*. A technical system consists of *sub-assemblies* and *components*, put together in a way that performs the required task, as in the breakdown of Fig. 1.3. It is like describing a cat (the system) as made up of one head, one body, one tail, four legs, etc. (the sub-assemblies), each composed of components—femurs, quadriceps, claws, fur. This decomposition is a useful way to analyze an existing design, but it is not of much help in the design process itself, that is, in devising new designs.

Better, for this purpose, is one based on the ideas of systems analysis. Think of the inputs, flows and outputs of information, energy, and materials, as in Fig. 1.4. The design converts the inputs into the outputs. An electric motor converts electrical into mechanical energy; a forging press takes and reshapes material and a burglar alarm collects information and converts it to noise. In this approach, the system is broken down into connected sub-systems, each of which performs a specific function. The resulting arrangement is called the *function-structure* or *function decomposition* of the system. It is like describing the cat as an appropriate linkage of a respiratory system, a cardiovascular system, a nervous system, a digestive system, and so on. Alternative designs link the unit

**FIGURE 1.3**

The analysis of a technical system as a breakdown into assemblies and components. Material and process selection is at the component level.

**FIGURE 1.4**

The function structure of a technical system showing the transformation of energy, materials, and information (signals) to achieve a final desired function.

functions in alternative ways, combine functions, or split them. The function-structure gives a systematic way of assessing design options.

Referring back to Fig. 1.2 the design proceeds by developing concepts to perform the functions in the function structure, each based on a *working principle*. At this stage, that is, the conceptual design stage, all options are open: the designer considers alternative concepts and the ways in which these might

be separated or combined. The next stage, embodiment, takes the promising concepts and seeks to analyze their operation at an approximate level. This involves sizing the components and selecting materials that will perform properly in the ranges of stress, temperature, and environment suggested by the design requirements, examining the implications for performance and cost. The embodiment stage ends with a feasible layout, which is then passed to the detailed design stage. Here specifications for each component are drawn up. Critical components may be subjected to precise mechanical or thermal analysis. Optimization methods are applied to components and groups of components to maximize performance. A final choice of geometry and material is made, and the methods of production are analyzed and costed. The stage ends with a detailed production specification.

All that sounds well and good. If only it were so simple. The linear process suggested by Fig. 1.2 obscures the strong coupling between the three stages. The consequences of choices made at the concept or embodiment stages may not become apparent until the detail is examined. Iteration, looping back to explore alternatives, is an essential part of the design process. Think of each of the many possible choices that *could* be made as an array of blobs in design space as suggested by Fig. 1.5. Here C1, C2 ... are possible concepts, and

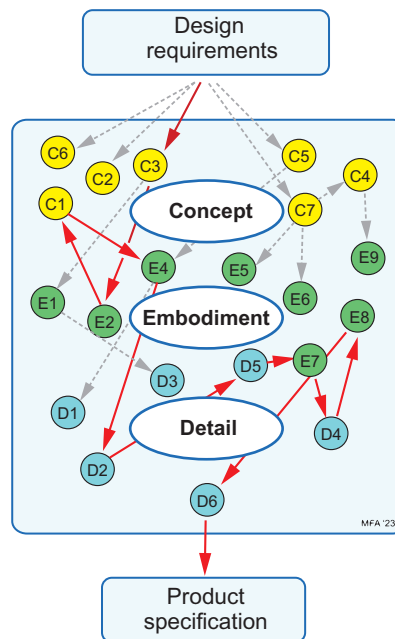


FIGURE 1.5

The convoluted path of design.

E1, E2 ... and D1, D2 ... are possible embodiments and detailed elaborations of them. The design process explores paths linking compatible blobs until a connection is made from the top (“Market need”) to the bottom (“Product specification”), shown as the red path in Fig. 1.5. Some trial paths have dead-ends, and some loop back—the broken grey lines. It is like finding a track across difficult terrain—it may be necessary to go back if, in the end, one is to go forward. Once a path is found, it is always possible to make it look linear and logical (and many books do this), but the reality is more like Fig. 1.5 than Fig. 1.2. Thus a key part of design and of selecting materials for it is *flexibility*, the ability to explore alternatives quickly, keeping the big picture as well as the details in mind.

Our focus in later chapters is on the selection of materials and processes, where exactly the same need arises. This requires some kind of mappings of the “universes” of materials and processes to allow quick surveys of alternatives while still providing detail when it is needed. The selection charts of Chapter 3 and the methods of Chapters 4 and 6 help do this.

Described in the abstract, these ideas are not easy to grasp. An example will help—it comes in Section 1.7. First, a look at types of design.

1.4 TYPES OF DESIGN

Original design starts from a new idea or working principle (the ball-point pen, the compact disc). New materials can offer new, unique combinations of properties that enable original design. Thus high-purity silicon enabled the transistor; high-purity glass the optical fiber; high coercive-force magnets the miniature earphone and solid-state lasers the compact disk. Sometimes the new material suggests the new product; sometimes, instead, the new product demands the development of a new material: nuclear technology drove the development of new zirconium alloys and low-carbon stainless steels; space technology stimulated the development of lightweight composites; and gas turbine technology today drives development of high-temperature alloys and ceramic coatings. Original design sounds exciting, and it is. But most design is not like that.

Almost all design is *adaptive* or *developmental*. The starting point is an existing product or product range. The motive for re-designing it may be to improve performance, to reduce cost, to meet environmental targets, or to adapt to changing market conditions. Adaptive design takes an existing concept and seeks refinement of the working principle. Often it is made possible by material developments: polymers replacing metals in household appliances and carbon fiber replacing wood in sports equipment. The appliance and sports equipment markets are fast moving and competitive. Markets here have frequently

been won (and lost) by the way in which the manufacturer has adapted the product by exploiting new materials.

Finally, *variant design* involves a change of scale or dimension or detailing without change of function or the method of achieving it. Change of scale or circumstances of use may require change of material: small boats are made of fiberglass, large ships are made of steel; small boilers are made of copper, large ones of steel; subsonic planes are made of one alloy, supersonic of another and for good reasons, detailed in later chapters.

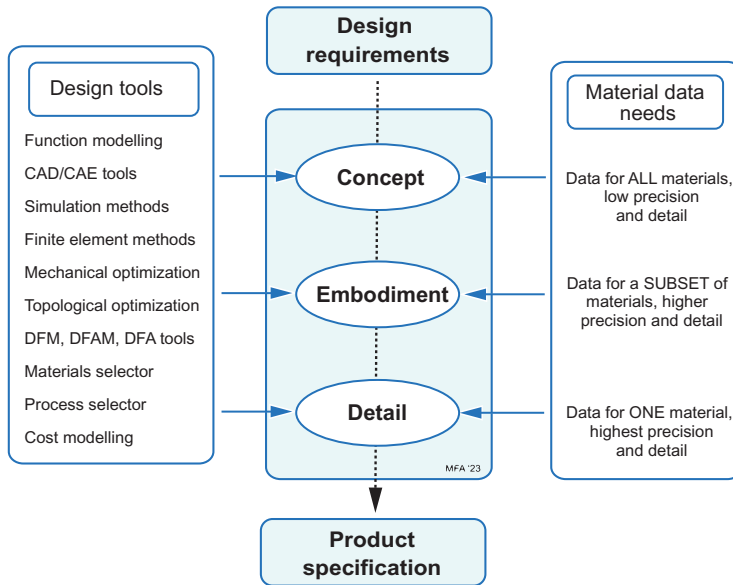
1.5 DESIGN TOOLS AND MATERIALS DATA

Tools exist to help with the steps of Fig. 1.2. They are shown as inputs, attached to the left of the main backbone of the design process of Fig. 1.6. Function-modelers suggest viable function structures. Configuration optimizers suggest or refine shapes. Geometric and 3-D solid modeling packages allow visualization and create files that can be downloaded to numerically controlled prototyping and manufacturing systems. Optimization, DFM, DFAM, DFA,¹ and cost estimation software products allow manufacturing aspects to be refined. Finite element (FE) and computational fluid dynamics (CFD) packages allow precise mechanical and thermal analysis even when the geometry is complex, deformations are large, and temperatures fluctuate. There is a natural progression in the use of the tools as the design evolves: approximate analysis and modeling at the conceptual stage; more sophisticated modeling and optimization at the embodiment stage; and precise (“exact”—but nothing is ever really that) analysis at the detailed design stage.

Tools for material selection are involved in each of the three stages. The nature of the data needed in the early stages differs greatly in its level of precision and breadth from that needed later (Fig. 1.6, *right side*). At the concept stage, only approximate property values are needed, but for the widest possible range of materials. All options are open: a polymer may be the best choice for one concept, a metal for another, even though the function is the same. The problem, at this stage, is not precision; it is breadth and speed of access: how can the vast range of data be scanned to maximize freedom of choice?

At the embodiment stage the landscape narrows. Here we need data for a subset of materials, but at a higher level of precision and detail. These are found in more specialized handbooks and software that deal with a single class or sub-class of materials—*metals*, or just *aluminum alloys*, for instance. The risk now is that of losing sight of the bigger spread to which we must return if the details don’t work out. It is easy to get trapped in a single line of thinking—a

¹ DFM, Design for Manufacture; DFAM, Design for Additive Manufacture; DA, Design for Assembly. All are discussed in Chapters 7 and 8.

**FIGURE 1.6**

The design flow chart, showing how design tools and materials selection enter the procedure. Information about materials is needed at each stage, but at different levels of breadth and precision.

single set of “connections” in the sense of Fig. 1.5—when other connections offer a better solution.

The final stage, that of detailed design, requires a still higher level of precision and detail, but for only one or a very few materials. Such information is best found in the datasheets issued by the material producers themselves and in detailed databases for restricted material classes. A given material (polyethylene, for instance) has a range of properties that derive from differences in the ways different producers make it. At the detailed design stage, a supplier must be identified, and the properties of their product used in the design calculations; that from another supplier may differ. And sometimes even this is not good enough. If the component is a critical one (meaning that its failure could, in some sense or another, be disastrous), then it is sensible to conduct in-house tests to measure the critical properties, using samples of the material that will be used for the product itself.

The materials input does not end with the establishment of production. Products fail in service, and failures contain information. It is an imprudent manufacturer that does not collect and analyze data on failures. Often this points to the misuse of a material, one that re-design or re-selection can eliminate.

So material choice depends on *function*. But that is not the only constraint.

1.6 FUNCTION, MATERIAL, SHAPE, AND PROCESS

The selection of material cannot be separated from those of process and shape. To make a shape, the material is subjected to processes that, collectively, we shall call *manufacture*: they include primary forming processes (like casting and forging), material removal processes (machining, drilling), joining processes (welding, for example), and finishing processes (such as painting or electroplating). Function, material, shape, and process interact (Fig. 1.1). Function, as we have just seen, influences material choice. Material choice influences processes through its ability to be cast or molded or welded or heat treated. Process determines the shape, size, precision, and, of course, cost. The interactions are two way: specification of shape restricts the choice of material and process, but equally the specification of process limits the materials choice and the accessible shapes. The more sophisticated the design, the tighter the specifications and the greater the interactions.

The interaction between function, material, shape, and process lies at the heart of the material selection process. It is a theme we return to throughout the book, visiting each of the hexagons of Fig. 1.1 in turn. But first, a case study to illustrate the design process.

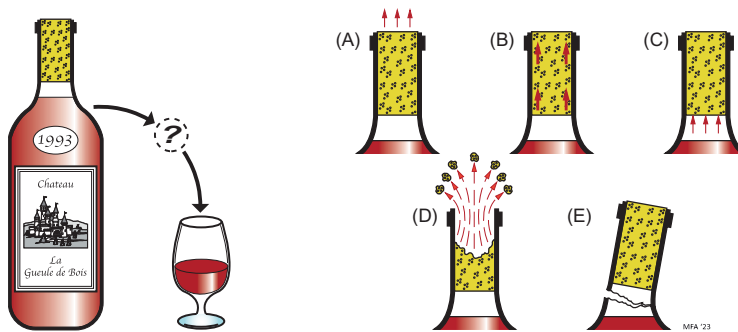
1.7 CASE STUDY: DEVICES TO OPEN CORKED BOTTLES

Wine, like cheese, is one of man's improvements on nature. And ever since humans have cared about wine, they have cared about cork to keep it safely sealed in flasks and bottles. "Corticum ... demovebit amphorae ..."—"Uncork the amphora ..."—sang Horace² to celebrate the anniversary of his miraculous escape from death by a falling tree in 27 BCE. But how did he do it?

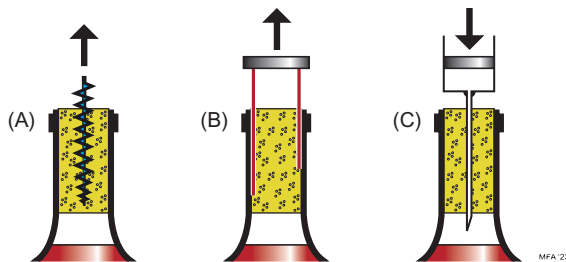
A corked bottle creates a market need: the need to gain access to the wine inside. We might state it thus: "a device is required to pull corks from wine bottles." But hold on. The need must be expressed in solution-neutral form, and this is not. The aim is to gain access to the wine; our statement implies that this will be done by removing the cork, and that it will be removed by pulling. There could be other ways. So we will try again: "a device is required to allow access to wine in a corked bottle" (Fig. 1.7), and one might add "with convenience, at modest cost and without contaminating the wine."

Five concepts for doing this are shown on the right of Fig. 1.7. In order, the devices act to remove the cork by axial traction (= pulling); to remove it by applying shear tractions to its sides; to push it out from below; to pulverize it;

² Horace, Q. 27 BC, Odes, Book III, Ode 8, line 10.

**FIGURE 1.7**

The market need, a device is sought to allow access to wine contained in a corked bottle (*left*). Five possible concepts to fill the need, illustrating physical principles (*right*).

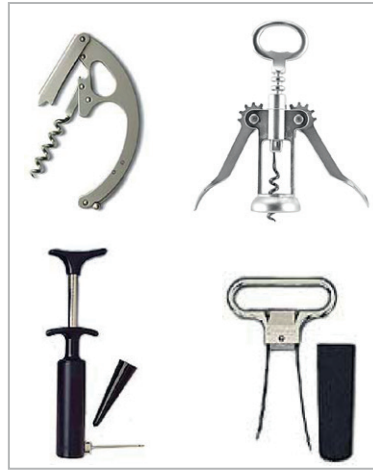
**FIGURE 1.8**

Working principles for implementing the first three concepts of Fig. 1.7.

and to by-pass it altogether by knocking the neck off the bottle.³ Numerous devices exist that use the first three concepts. The others are used too, though generally only in moments of desperation. We'll eliminate these on the grounds that they might contaminate the wine and focus on the others, exploring working principles.

Fig. 1.8 suggests embodiments for the surviving concepts. In the first, a screw is threaded into the cork to which an axial pull is applied. In the second, slender elastic blades inserted down the sides of the cork apply shear tractions when twisted and pulled. In the third the cork is pierced by a hollow needle through which a gas is pumped to push the cork out. All have been developed to the detailed stage and entered production (Fig. 1.9).

³A Victorian invention for opening well-aged port, the cork of which may become brittle with age and alcohol absorption, involved ring-shaped tongs. The tongs were heated red on an open fire, then clamped onto the cold neck of the bottle. The thermal shock removed the neck cleanly and neatly.

**FIGURE 1.9**

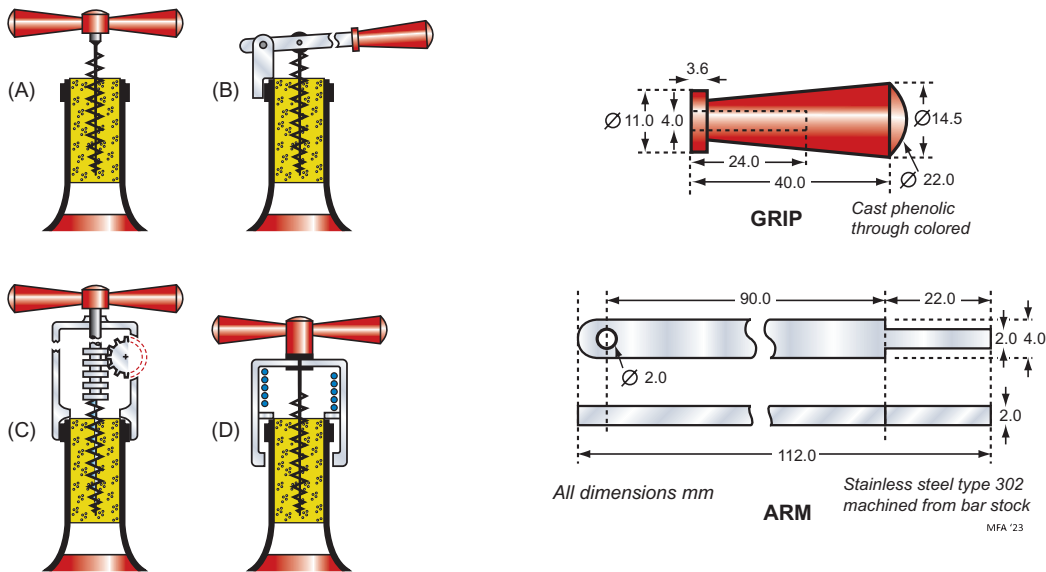
Cork removers, clockwise from top left: levered pull, geared pull, shear traction (sounds weird but it works), and pressurized expulsion (now rare—the risks are too great).

Fig. 1.10, *left*, shows more detailed embodiments for devices based on just one concept—that of axial traction. The first is a direct pull; the other three use some sort of mechanical advantage—levered pull, geared pull, and spring-assisted pull. The embodiments identify the *functional requirements* of each component of the device, which might be expressed in statements like:

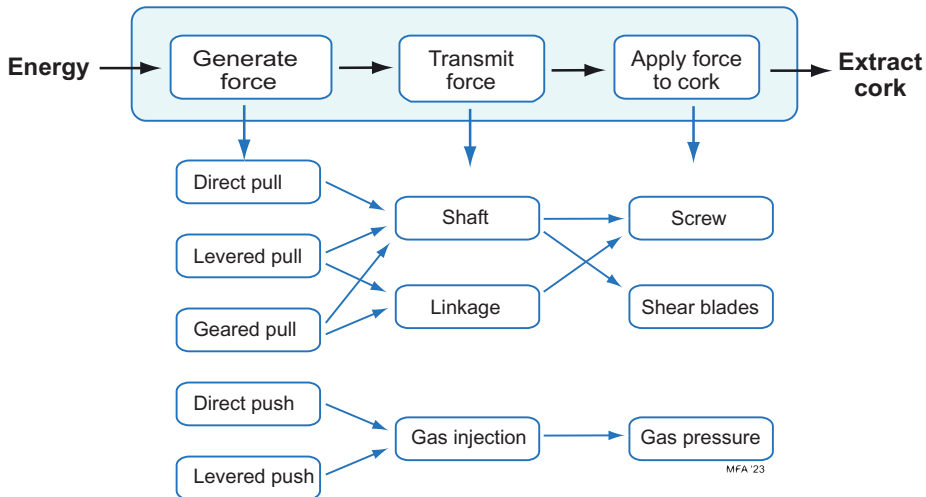
- a cheap screw to transmit a prescribed load to the cork,
- a light lever (that is, a beam) to carry a prescribed bending moment,
- a slender elastic blade that will not buckle when driven between the cork and bottle neck,
- a thin, hollow needle, stiff, strong, and sharp enough to penetrate a cork and so on.

The functional requirements of each component are the inputs to the materials selection process. They lead directly to the *property limits* and *material indices* of Chapter 4. The procedure developed there takes requirements such as “light, strong, beam” or “slender, elastic, blade” and uses them to identify a subset of materials that will perform this function particularly well. The final choice of material and process forms part of the detailed stage of design (Fig. 1.10, *right*), leading to a full specification to enable manufacture.

We conclude by returning to the idea of function-structure. That for the cork remover is sketched in the upper part of Fig. 1.11: generate a force, transmit a force, and apply force to cork. The alternative designs differ in the working principle by which these functions are achieved, as indicated in the lower part of the figure. Others could be devised by making other links.

**FIGURE 1.10**

Embodiments: (A) direct pull; (B) lever-assisted pull; (C) gear-assisted pull; and (D) spring-assisted pull. Detailed design of the lever of embodiment (B), with material choice (*right*).

**FIGURE 1.11**

The function-structure and working principles of cork removers.

1.8 SUMMARY AND CONCLUSIONS

Design is an iterative process. The starting point is a *market need* captured in a set of *design requirements*. *Concepts* for a product that meet the need are devised. If an initial analysis suggests that a concept is viable, the design proceeds to the *embodiment* stage: working principles are selected, size and layout are decided, and initial estimates of performance and cost are made. If the outcome is successful, the designer continues to the *detailed design* stage: optimization of performance; full analysis of critical components; preparation of detailed production drawings (usually as CAD files); and specification of tolerance, precision, assembly, and finishing methods.

Materials selection enters at each stage, but at different levels of breadth and precision. At the conceptual stage all materials and processes are potential candidates, requiring a procedure that allows rapid access to data for a wide range of each, although without the need for great precision. The preliminary selection passes to the embodiment stage, the calculations and optimizations of which require information at a higher level of precision and detail. They eliminate all but the short-listed materials and processes for the final, detailed stage of the design. For these few, the need is for data of the highest quality.

Data exist that meet the needs of all these levels. Each level requires its own data management scheme, described in the following chapters. The management system must be design led and yet must recognize the richness of choice and embrace the complex interaction between the material, its shape, the process by which it is given that shape, and the function it is required to perform. And it must allow rapid iteration—back-looping when a particular path proves to be unprofitable. Tools now exist to help with all of this. We will meet one—the Ansys Granta materials and process selection platform—later in this book.

But given this complexity, why not opt for the safe bet: stick to what you used before? Many have chosen that option. Fewer are still in business.

1.9 FURTHER READING

A chasm exists between books on design methodology and those on materials selection: each largely ignores the other. Pahl and Beitz have near-biblical standing in the design camp, but their approach is heavy going. Ullman and Cross take a more relaxed approach and are easier to digest. On the materials side, the books by Callister, Shackelford, Askeland, Budinski, and Budinski and by Farag present the materials case well but pay less attention to design. The best compromise, perhaps, is Dieter.

General Texts on Design Methods

- Cross, N., 2021. Engineering Design Methods, 5th edition. Wiley, Chichester UK. ISBN 978-1-119-72437-7. (*A durable text describing the design process, with emphasis on developing and evaluating alternative solutions.*) <https://www.wiley.com/en-gb/Engineering+Design+Methods%3A+Strategies+for+Product+Design%2C+5th+Edition-p-9781119724407>
- Dieter, G.E., 2000. Engineering Design, a Materials and Processing Approach, 3rd edition. McGraw-Hill, New York, USA, 150–153 and 255–257. ISBN 0-07-366136-8. (*A well-balanced and respected text, now in its 3rd edition, focusing on the role of materials and processing in technical design.*)
- Dieter, G.E., Schmidt, L.C., 2012. Engineering Design, 5th edition. McGraw Hill, NY, USA. ISBN 978-0073398143. (*A clear introduction from authors with a strong materials background.*) <https://vdoc.pub/download/engineering-design-5th-edition-ehf1e2dc2ha0>
- Pahl, G., Beitz, W. Feldhusen, J. and Grote, K.-H., 2007. Engineering Design, 3rd edition, translated by K. Wallace and L. Blessing, Springer Verlag, Berlin, Germany. ISBN 978-1-4471-6025-0. (*The Bible—or perhaps more exactly the Old Testament—of the technical design field, developing formal methods in the rigorous German tradition.*)
- Ullman, D.G., 2009. The Mechanical Design Process, 4th edition. McGraw-Hill, NY, USA. ISBN 978-0072975741. (*An American view of design, developing ways in which an initially ill-defined problem is tackled in a series of steps, much in the way suggested by Fig. 1.1 of the present text.*)
- Ulrich, K.T., 2011. Design—Creation of Artefacts in Society. The University of Pennsylvania, USA. ISBN 978-0-9836487-0-3. (*An excellent short introduction to the kind of structured reasoning that lies behind good product design. The text is available at <http://www.ulrichbook.org/>*)
- Ulrich, K.T., Eppinger, S.D., Yang, M.C., 2019. Product Design and Development, 7th Edition. McGraw Hill, NY, USA. ISBN 978-9390113231 (*A readable, comprehensible text on product design, as taught at MIT. Many helpful examples but almost no mention of materials.*)

General Texts on Materials Selection in Design

- Asby, M.F., Shercliff, H.R., Cebon, D., 2023. Introduction to Materials Science and Engineering. Butterworth Heinemann, Oxford, UK. ISBN: 978-0081023990 (*An elementary text introducing materials through material property charts, and developing the selection methods through case studies.*)
- Askeland, D.R., Phulé, P.P., Wright, W.J., 2015. The Science and Engineering of Materials, 7th edition. Thomson, Toronto, Canada. ISBN 978-1305077102. (*A well-established materials text that deals well with the science of engineering materials.*)
- Budinski, K.G., Budinski, M.K., 2010. Engineering Materials, Properties and Selection, 9th edition. Prentice Hall, NY, USA. ISBN 978-0136109501. (*Like Askeland, this is a well-established materials text that deals well with both material properties and processes.*)
- Callister, W.D., Rethwisch, D.G., 2020. Materials Science and Engineering: An Introduction, 10th edition. John Wiley & Sons, New York, USA. ISBN-13: 978-1119321590. (*A well-established text taking a science-led approach to the presentation of materials teaching.*)
- Farag, M.M., 2020. Materials and Process Selection for Engineering Design, 4th edition. CRC Press, Taylor and Francis, London, UK. ISBN 978-0367419479. (*A Materials-Science approach to the selection of materials.*)
- Fischer, T., 2008. Materials Science for Engineering Students. Academic Press. ISBN 978-012373587. (*Fischer distinguishes structural materials and functional materials rather than emphasizing structural materials alone, with focus on newer classes of materials, such as ceramics, polymers and composites.*)
- Shackelford, J.F., 2021. Introduction to Materials Science for Engineers, 9th edition. Pearson, NJ, USA. ISBN 978-0136912453. (*A well-established materials text with a materials and design slant.*)

And on Corks and Corkscrews

- Ellis, F., 2009. Corkscrews. The Crowood Press Ltd, Marlborough, UK. ISBN 9781847971135. (*Ingenious ways to remove corks from bottles using the laws of physics, the skills of mechanical engineering and the science of new materials.*)
- McKearin, H., 1973. On "Stopping," Bottling and Binning. International Bottler and Packer, Binsted Group Ltd, Editorial & Publications, Farnham, UK, pp. 47–54 April.
- Perry, E., 1980. Corkscrews and Bottle Openers. Shire Publications Ltd, Aylesbury, UK.
- Watney, B.M., Babbage, H.D., 1981. Corkscrews. Sotheby's Publications, London, UK. ISBN 0-85667-113-4

1.10 EXERCISES

- E1.1. Concepts (working principles).** Even if you shut the windows and doors dust settles in rooms like gentle snow. The need: a device to remove dust from household floors. Here are three established concepts:
- human-powered bellows pump with cloth filter;
 - axial-flow electric fan with muslin filter; and
 - centrifugal fan with centrifugal dust separation and collection.
- What other concepts could fill this need? Nothing, at the concept stage, is too farfetched. Decisions about practicality and cost come later.
- E1.2. Function structures.** Make a function-structure diagram for the Electrolux cleaner in Fig. 1.12.



FIGURE 1.12

Vacuum cleaners: a hand-powered cleaner from 1880, the Electrolux cylinder cleaner of 1960, and the Dyson centrifugal cleaner of 2022.

E1.3. Concepts (working principles) for cooling power electronics.

Microchips, particularly those for power electronics, get hot. If they get too hot, they cease to function. The need: a scheme for removing heat from power microchips. One is sketched in Fig. 1.13. Its working principle is that of thermal conduction to fins from which heat is removed by convection.

Heat can be removed in four ways (the working principles):

- thermal conduction,
- convection,
- exploiting a phase change, and
- radiation.

The best solution for the microchip may be found by combining two or more of these, such as conduction coupled with convection, as in Fig. 1.13. Suggest other combinations (a) for continuous operation and (b) for short-term, intermittent operation.

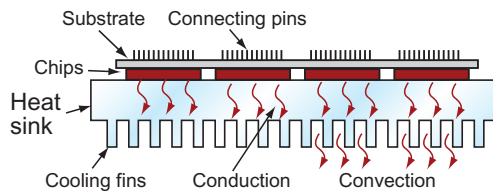


FIGURE 1.13

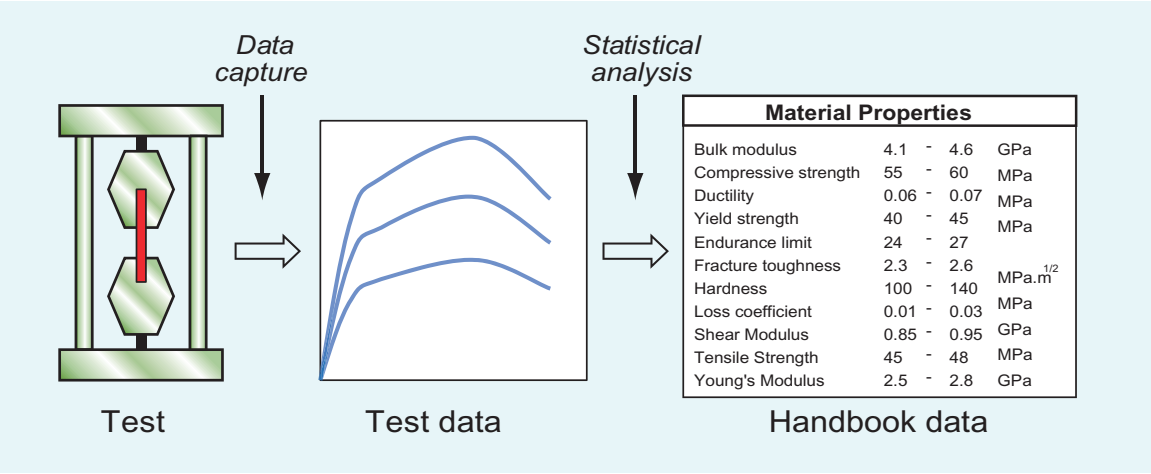
A heat sink.

E1.4. Function structures. Make a function-structure diagram for heat sinks.

E1.5. Attaching paper sheets. The need: multi-page documents can get muddled if the pages are loose. Use the internet to explore alternative concepts for attaching a small number of pages together in a way that still allows them to be read. Record, as far as possible, the materials of the attachment and the property that provides the attachment force.

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Engineering Materials and Their Properties



2.1 INTRODUCTION AND SYNOPSIS

Materials, you might say, are the food of design. This chapter presents the menu: the materials shopping list. A successful product—one that performs well, is good value for money, and gives pleasure to the user—uses the materials best suited for the job and exploits their potential and characteristics. Brings out their flavor, so to speak.

The families of materials—metals, polymers, ceramics, and so forth—are introduced in [Section 2.2](#). What do we need to know about them if we are to design with them? That is the subject of [Section 2.3](#), in which distinctions are drawn between various types of materials information. But it is not, in the end, a *material* that we seek; it is a certain *profile of properties*—the profile that best meets the needs of the design. Properties are the currency of the materials world. They are the bargaining chips—the way you trade off one material against another. The properties important in thermo-mechanical design are

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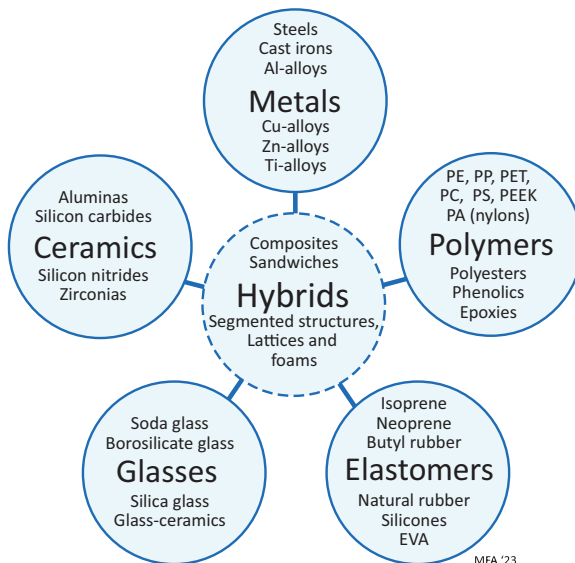
defined briefly in [Section 2.4](#). It makes boring reading. The reader who is confident in the definitions and units of moduli, strengths, damping capacities, thermal and electrical conductivities and the like, may wish to skip this, using it for reference when needed.

This chapter—and particularly the exercises at the end of it—serve another purpose. It is to introduce two of the three Appendices that you will find at the end of the book. The first is a compilation of material properties set out in a consistent way that makes it easy to use. The second is compilation of solutions to standard problems of mechanics and heat flow. Fluency in their use is a real asset; it gives the confidence that comes when, although you don't know a solution, you do know where to find it. We will draw on these Appendices repeatedly in the chapters that follow.

The chapter ends, in the usual way, with a Summary and Further Reading.

2.2 THE FAMILIES OF ENGINEERING MATERIALS

It is conventional to classify the materials of engineering into the six broad families shown in [Fig. 2.1](#): metals, polymers, elastomers, ceramics, glasses, and hybrids. The members of a family have certain features in common: similar properties, similar processing routes, and, often, similar applications.



MFA '23

FIGURE 2.1

The menu of engineering materials. The basic families of metals, polymers, elastomers, ceramics, and glasses can be combined to create hybrids.

Metals are stiff—they have relatively high elastic moduli. They are good conductors of heat and electricity. When pure, they are soft and easily deformed. They can be made stronger by alloying and by mechanical and thermal treatment, but they remain ductile, allowing them to be shaped by deformation processes. Certain high-strength alloys (spring steel, for instance) have ductilities as low as 1%, but even this is enough to ensure that the material yields before it fractures and that fracture, when it occurs, is of a tough, ductile type. Partly because of their ductility, metals are prey to fatigue, and of all material classes they are the least resistant to corrosion.

Polymers are at the other end of the spectrum. They have moduli that are low, roughly 50 times less than those of metals, but they can be strong. A consequence of this is that elastic deflections can be large. They creep, even at room temperature, meaning that a polymer component under load may, with time, acquire a permanent set. And their properties depend on temperature so that a polymer that is tough and flexible at 20°C may creep rapidly at the 100°C of boiling water yet be brittle at the 4°C of a household refrigerator. Few have useful strength above 200°C. Some polymers are partly crystalline; others are amorphous (non-crystalline)—the transparent ones are amorphous. If allowance is made for these, the advantages of polymers can be exploited. And there are many. When combinations of properties, such as strength-per-unit weight, are important, polymers can compete with metals. They are easy to shape. Complicated parts performing several functions can be molded from a polymer in a single operation. The large elastic deflections allow the design of polymer components that snap together, making assembly fast and cheap. And by accurately sizing the mold and pre-coloring the polymer, no finishing operations are needed. Polymers resist corrosion (paints, for instance, are polymers) and have low coefficients of friction. Good design exploits these properties.

Elastomers are long-chain polymers above their glass-transition temperature, T_g . The covalent bonds that link the units of the polymer chain remain intact, but the weaker Van der Waals and hydrogen bonds that, below T_g , bind the chains to each other, have melted. This gives elastomers unique properties: their elastic moduli are as low as 1 MPa (10^5 times less than that typical of metals), and they are capable of enormous elastic extension. Their properties differ so much from those of other solids that special tests have evolved to characterize them. This creates a problem: if we wish to select materials by prescribing a desired attribute profile, as we do later in this book, then a prerequisite is a set of attributes common to them all. To overcome this, we use a common set of properties in the early stages of design, estimating approximate values for anomalies like elastomers. Specialized attributes, representative of one family only, are used in the later stages.

Ceramics, like metals, have high moduli, but, unlike metals, they are brittle. Their “strength” in tension means the brittle fracture strength; in compression

it is the brittle crushing strength, which is about 15 times greater. And because ceramics have no ductility, they have a low tolerance for stress concentrations like holes or cracks, or for high contact stresses, at clamping points, for instance. Ductile materials accommodate stress concentrations by deforming in a way that redistributes the load more evenly, and because of this, they can be used under static loads within a small margin of their yield strength. The brittleness of ceramics makes design with them more difficult than design with metals. Despite this, they have attractive features. They are stiff, hard, and abrasion-resistant (hence their use for bearings and cutting tools); they retain their strength to high temperatures (they are used as thermal-barrier coatings on aircraft turbine blades); and they resist corrosion well (thus their use as toilets, basins, and kitchen work-surfaces).

Glasses are non-crystalline (“amorphous”) solids. The most common are the soda-lime and borosilicate glasses familiar as bottles and ovenware, but there are many more. The lack of crystal structure suppresses plasticity, so, like ceramics, glasses are hard, brittle, and vulnerable to stress concentrations. In sheet form, glasses are strengthened by treatments that introduce a compressive stress into the near-surface layers, preventing any crack that forms there from spreading.

Hybrids are combinations of two or more materials in a pre-determined configuration and scale. The best of them combine the attractive properties of the other families of materials while avoiding some of their drawbacks. The family of hybrids includes fiber and particulate composites, sandwich structures, lattice structures, foams, cables and laminates, and almost all the materials of nature—wood, bone, leaf, and skin. Fiber-reinforced composites, widely used in engineering, have a polymer matrix reinforced by fibers of glass, carbon, or Kevlar (an aramid). They are light, stiff, and strong, and they can be tough. They, and other hybrids using a polymer as one component, cannot be used above 250°C because the polymer softens, but at room temperature their performance can be outstanding. Hybrids tend to be expensive and can be difficult to shape and join. So, despite their attractive properties, the designer will use them only when the added performance justifies the added cost. Today’s emphasis on vehicle fuel efficiency and performance provides increasing incentives to use them.

These, briefly, are the material families. What do we need to know about them?

2.3 MATERIALS INFORMATION FOR DESIGN

The engineer, in selecting materials for a developing design, needs data for their properties. Engineers are often conservative in their choice, reluctant to consider materials with which they are unfamiliar, and with good reason. Data

for the old, well-tried materials are reliable and easily found. Data for newer, emerging, materials may be incomplete or untrustworthy. Yet innovation is often made possible by new materials. So it is important to know how to judge data quality.

If you're going to design something, what sort of materials information do you need? Fig. 2.2 draws relevant distinctions. On the left a material is tested and the *raw data* are captured. But this raw data—unqualified numbers—are, for our purposes, useless. To make data useful requires statistical confidence. What is the mean value of the property when measured on a large batch of samples? What is the standard deviation? Given this it is possible to calculate *allowables*, values of properties that, with a given certainty (say, one part in 10^6) can be guaranteed. Material texts generally present test data; by contrast, data in most engineering handbooks are allowables.

Think of data with known precision and provenance as *information*, numbers that mean something. Data of this sort can be assembled as tables, as yes/no statements or as rankings: that is, it can be *structured*. Many properties that can be structured are common to all materials; all, for instance, have a density, an elastic modulus, a strength, and a thermal conductivity. Structured information can be stored in a database and—since all materials have values—it is the starting point for selecting between them.

This is a step forward, but it is not enough. To design with a material, you need to know its real character, its strengths, and its weaknesses. What does it cost? How do you shape it? How join it? How long will it last? Who has used it before and for what? Did it perform well or give problems? Does its use damage the environment? This information is documented in handbooks as design guidelines, failure analyses, and case studies. It consists largely of text, graphs,

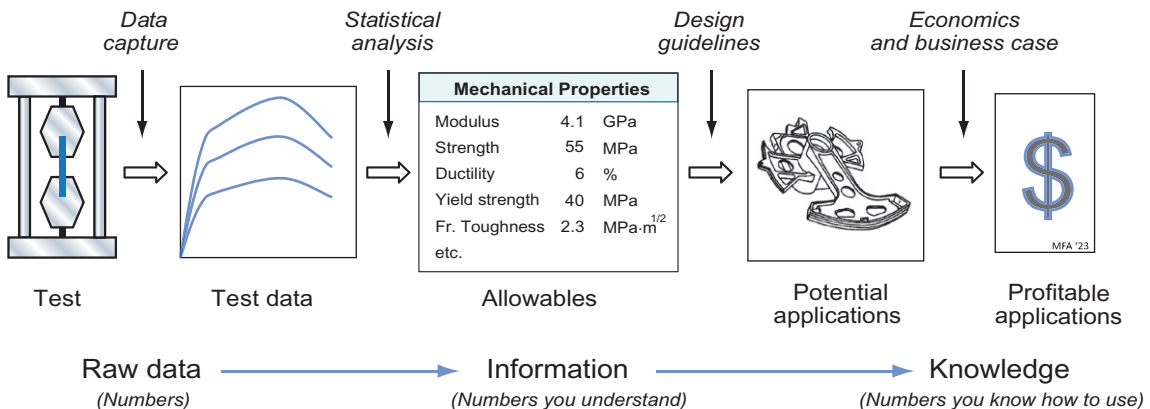


FIGURE 2.2

Types of material information.

and images, and while certain bits of it may be available for one material, for another they may not. We refer to this unstructured data as *documentation*, the character profile of the material. It's like getting to know a new member of your team. To use them effectively, you have to know how they will respond to the situations to which they'll be exposed.

There is more. Material uses are subject to standards and codes. These rarely refer to a single material but to classes or subclasses. For a material to be used in contact with food or drugs, it must carry FDA approval or the equivalent. Metals and composites for use in US military aircraft must have Military Specification qualification. The ISO 14040 set of Standards stipulates eco-requirements required to meet ISO approval. And so forth. This, too, is a form of documentation.

The combination of structured and documentation for a material constitutes *knowledge*—numbers that you know how to use.

There is yet more (Fig. 2.2, right side). To succeed and be profitable in the marketplace, a product must offer a combination of performance, consumer appeal and cost that single it out. All of these depend on material choice and the way the material is processed. Much can be said about this, but not here—we return to it in Chapter 7. For now, the focus is on structured data and documentation.

That's the essential background. Now for the properties themselves.

2.4 MATERIAL PROPERTIES AND THEIR UNITS

Materials have properties: mechanical, thermal, electrical, and environmental. The set that characterizes a given material is its *property profile*. Property profiles are assembled by systematic testing. In this section we scan the nature of the tests and the definition and units of the properties. Units are given here in the SI system. Conversion factors to other systems are printed on the inside front and back cover of this book.

Appendix A of this book is a compilation of property profiles for 63 widely used materials. Appendix B lists solutions to standard, often-recurring, problems that use them.

2.4.1 Density and Price (Appendix A, Table A.2)

Property	Symbol and Units
Density	ρ (kg/m ³)
Price	C_m (\$/kg)

Density. The *density*, ρ (units: kg/m³), is the mass per unit volume. We measure it today as Archimedes did: by weighing in air and in a fluid of known density.

Price. The price, C_m (units: \$/kg), of materials spans a wide range. Some cost as little as \$0.2/kg, others more than \$1000/kg. Prices fluctuate, and they depend on the quantity you want and on your status as a “preferred customer” with your chosen vendor. Despite this uncertainty, it is useful to have an approximate price, which is useful in the early stages of material selection.

2.4.2 Mechanical Properties (Appendix A, Tables A.3–A.5. In use: Appendix B, Tables B.3–B.13)

Property	Symbol and Units
Elastic moduli (Young's, Shear, Bulk)	E, G, K (GPa)
Yield strength	σ_y (MPa)
Tensile (ultimate) strength	σ_{ts} (MPa)
Compressive strength	σ_c (MPa)
Failure strength	σ_f (MPa)
Hardness	H (Vickers)
Elongation	ε (–)
Fatigue endurance limit	σ_e (MPa)
Fracture toughness	K_{Ic} (MPa · m ^{1/2})
Toughness	G_{Ic} (kJ/m ²)
Loss coefficient (damping capacity)	η (–)
Wear rate (Archard) constant	K_A MPa ^{–1}

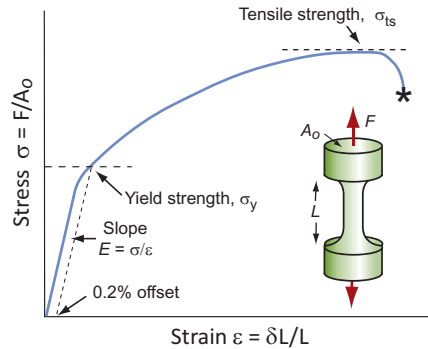
Elastic modulus. The elastic modulus E (units: GPa or GN/m²) is the slope of the initial, linear-elastic, part of the stress–strain curve (Fig. 2.3). Young's modulus, E , describes response to tensile or compressive loading, the shear modulus, G , describes response to shear loading and the bulk modulus, K , response to hydrostatic pressure. Poisson's ratio, ν , is the negative of the ratio of the lateral strain, ε_2 , to the axial strain, ε_1 , in axial loading:

$$\nu = -\frac{\varepsilon_2}{\varepsilon_1}$$

In reality, moduli measured as slopes of stress–strain curves are inaccurate, often low by a factor of 2 or more, because of contributions to the strain from anelasticity, creep, and other factors. Accurate moduli are measured dynamically: by exciting the natural vibrations of a beam or wire, or by measuring the velocity of sound waves in the material.

In an isotropic material, the moduli are related in the following ways:

$$E = \frac{3G}{1 + G/3K}; \quad G = \frac{E}{2(1 + \nu)}; \quad K = \frac{E}{3(1 - 2\nu)} \quad (2.1)$$

**FIGURE 2.3**

A stress–strain curve showing the modulus, E , the 0.2% yield strength, σ_y , and the ultimate tensile strength σ_{ts} .

Commonly $\nu \approx 1/3$ when

$$G \approx \frac{3}{8}E \quad \text{and} \quad K \approx E \quad (2.2a)$$

Elastomers are exceptional. For these $\nu \approx 1/2$ when

$$G \approx \frac{1}{3}E \quad \text{and} \quad K \gg E \quad (2.2b)$$

Appendix A lists data for E . Use Eqs. (2.2) to estimate approximate values for the other moduli.

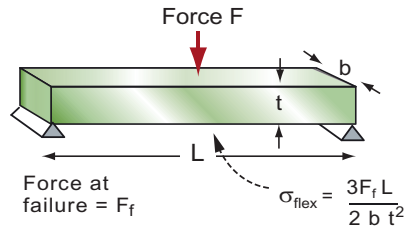
ESTIMATING MODULI

Young's modulus E for copper is 124 GPa, and its Poisson's ratio ν is 0.345. What is its shear modulus, G ?

Answer

Inserting the values for E and ν in the central Eq. [2.1] gives $G = 46.1$ GPa. The measured value is 45.6 GPa, a difference of 1%.

Strength. The strength, σ_f (units: MPa or MN/m²), of a solid requires careful definition. For metals, we identify σ_f with the 0.2% offset yield strength σ_y , that is, the stress at which the stress–strain curve for axial loading deviates by a strain of 0.2% from the linear-elastic line (Fig. 2.3). It is the same in tension and compression. For polymers, σ_f is identified as the stress at which the stress–strain curve becomes markedly non-linear, at a strain, typically, of 1%. This may be caused by shear-yielding: the irreversible slipping of molecular

**FIGURE 2.4**

The modulus-of-rupture (MOR) is the surface stress at failure in bending.

chains; or it may be caused by crazing: the formation of low-density, crack-like volumes that scatter light, making the polymer look white. Polymers are a little stronger in compression than in tension by a factor of about 1.2.

Strength, for ceramics and glasses, depends on how you load them. In tension, “strength” means the fracture strength, σ_t . In compression it means the crushing strength σ_c , which is much greater; typically

$$\sigma_c = 10 \text{ to } 15 \sigma_t \quad (2.3)$$

When a material is difficult to grip, as is a ceramic, its strength can be measured in bending. The flexural strength or modulus of rupture, σ_{flex} (units: MPa), is the maximum surface stress in a bent beam at the instant of failure (Fig. 2.4). One might expect this to be the same as the strength measured in tension, but for ceramics it is greater by a factor of about 1.3, because the volume subjected to this maximum stress and the probability of a large flaw lying in it are small.

The strength of a composite is best defined by a set deviation from linear-elastic behavior; often an offset of 0.5% is taken. Composites that contain fibers, including natural composites such as wood, are a little weaker (up to 30%) in compression than tension because fibers buckle. In subsequent chapters, σ_f for composites means the tensile strength.

Strength, then, depends on material class and on mode of loading. Other modes of loading are possible: shear, for instance. Yield under multi-axial loads is related to that in simple tension by a *yield function*. For metals, the Von Mises’ yield function is a good description:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_f^2 \quad (2.4)$$

where σ_1 , σ_2 , and σ_3 are the principal stresses, positive when tensile; σ_1 , by convention, is the greatest or most positive, σ_3 the smallest or least positive.

Sound travels through solids as an elastic wave. The longitudinal wave speed, v_s , is

$$v_s = \sqrt{E/\rho} \quad (2.5)$$

USING YIELD FUNCTIONS

A metal pipe of radius r and wall thickness t carries an internal pressure p . The pressure generates a circumferential wall-stress of $\sigma_1 = pr/t$ an axial wall-stress $\sigma_2 = pr/2t$. At what pressure will the pipe first yield?

Answer

Setting $\sigma_2 = \sigma_1/2$, $\sigma_3 = 0$, and $\sigma_f = \sigma_y$ in Eq. (2.4) gives the yield condition $\sigma_1 = (2/\sqrt{3})\sigma_y$.

Thus the pressure p^* that just causes first yield is $p^* = \frac{2}{\sqrt{3}} \frac{t}{r} \sigma_y$.

Tensile strength. The *tensile* (or *ultimate*) strength σ_{ts} (units: MPa) is the nominal stress at which a round bar of the material, loaded in tension, separates (Fig. 2.3). For brittle solids—ceramics, glasses, and brittle polymers—it is the same as the failure strength in tension. For metals, ductile polymers, and most composites, it is greater than the yield strength, σ_y , by a factor of between 1.1 and 3 because of work hardening or, in the case of composites, because of load transfer to the reinforcement.

Fatigue strength. Cyclic loading can cause a crack to nucleate and grow in a material, culminating, after N_f cycles, in fatigue failure. For many materials there exists a fatigue or *endurance limit*, σ_e (units: MPa), illustrated by the $\Delta\sigma$ – N_f curve of Fig. 2.5. It is the stress range $\Delta\sigma$ below which fracture does not occur, or occurs only after a very large number ($N_f > 10^7$) of cycles, when the

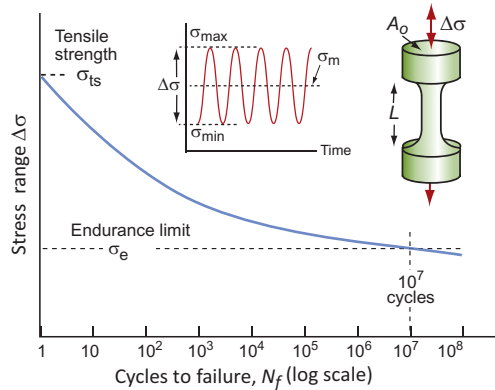


FIGURE 2.5

The endurance limit, σ_e , is the cyclic stress range that causes failure in $N_f = 10^7$ cycles.

mean stress $\sigma_m = 0$. The stress range $\Delta\sigma_{\sigma m}$ for failure under a mean stress σ_m , relative to that for failure at zero mean stress $\Delta\sigma_{\sigma 0}$, is:

$$\Delta\sigma_{\sigma m} = \Delta\sigma_{\sigma 0} \left(1 - \frac{\sigma_m}{\sigma_{ts}} \right). \quad (2.6)$$

where σ_{ts} is the tensile strength.

Hardness. Tensile and compression tests are not always possible: a large sample is needed and the test destroys it. An alternative is to measure the *hardness*, H (SI units: MPa), found by pressing a pointed diamond or hardened steel ball into the surface of the material. The hardness is defined as the indenter force divided by the area of the indent projected normal to the direction of indentation. It is related to the quantity we have defined as σ_y by

$$H \approx 3\sigma_y \quad (2.6)$$

This, in the SI system, has units of MPa, but it is commonly reported in a bewildering array of other units. The most common is the Vickers, H_v , scale with units of kg/mm². H_v is related to H by

$$H_v = \frac{H}{10} \quad (2.7)$$

Fig. 2.6 is a conversion chart for six hardness scales, relating them to yield strength (the last column).

STRENGTH FROM HARDNESS

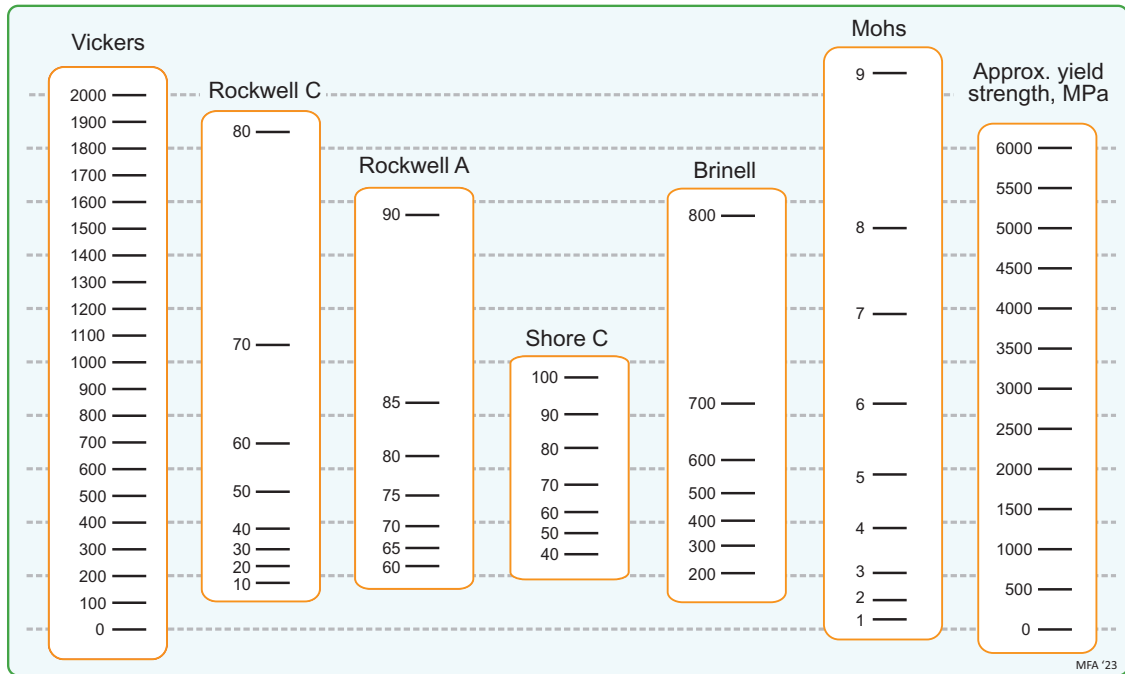
A steel has a hardness of 50 on the Rockwell C scale. Approximately what is its Vickers hardness and yield strength?

Answer

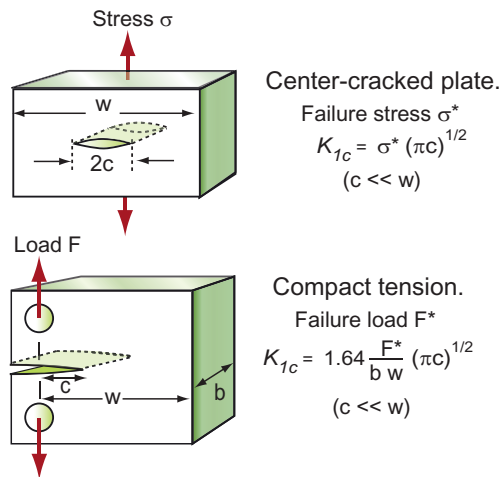
From Fig. 2.6, the Vickers hardness corresponding to a Rockwell C value of 50 is approximately $H_v = 500$ and the corresponding yield strength is approximately 1700 MPa.

Toughness and fracture toughness. The *toughness*, G_{1c} (units: kJ/m²), and the *fracture toughness*, K_{1c} (units: MPa · m^{1/2} or MN/m^{1/2}), measure the resistance of a material to the propagation of a crack. The fracture toughness is measured by loading a sample containing a deliberately introduced sharp crack of length $2c$ (Fig. 2.7), recording the tensile stress σ^* at which the crack propagates. The quantity K_{1c} is then calculated from

$$K_{1c} = Y\sigma^* \sqrt{\pi c} \quad (2.8)$$

**FIGURE 2.6**

Commonly used scales of hardness related to each other and to the yield strength.

**FIGURE 2.7**

Measuring fracture toughness, K_{Ic} .

and the toughness from

$$G_{1c} = \frac{K_{1c}^2}{E(1+\nu)} \quad (2.9)$$

Here Y is a geometric factor, near unity, that depends on details of the sample geometry, E is Young's modulus and ν is Poisson's ratio. Measured in this way K_{1c} and G_{1c} have well-defined values for brittle materials: ceramics, glasses, and brittle polymers. In ductile materials a plastic zone develops at the crack tip, introducing new features into the way in which cracks propagate that necessitate more involved characterization. Values for K_{1c} and G_{1c} are, nonetheless, cited and are useful as a way of ranking materials.

$$\sigma_c = K_{1c} / \sqrt{\pi c} = 339 \text{ MPa}.$$

USING FRACTURE TOUGHNESS

A glass floor panel contains micro-cracks up to 2 microns in length. Glass has a fracture toughness of $K_{1c} = 0.6 \text{ MPa} \cdot \text{m}^{1/2}$. When the panel is walked upon, stresses as high as 30 MPa appear in it. Is it safe?

Answer

The stress required to make a 2-micron crack (so $c = 10^{-6} \text{ m}$) propagate in glass with a fracture toughness of $K_{1c} = 0.6 \text{ MPa} \cdot \text{m}^{1/2}$, using Eq. [2.8] with $Y = 1$, is The panel is safe.

Mechanical loss coefficient. The *loss-coefficient* or *mechanical damping*, η (a dimensionless quantity), measures the degree to which a material dissipates vibrational energy. If a material is loaded elastically to a stress $\sigma_{\max}$, it stores an elastic energy

$$U = \int_0^{\sigma_{\max}} \sigma d\varepsilon \approx \frac{1}{2} \frac{\sigma_{\max}^2}{E}$$

per unit volume. If it is loaded and then unloaded, it dissipates an energy

$$\Delta U = \oint \sigma d\varepsilon$$

The loss coefficient is

$$\eta = \frac{\Delta U}{2\pi U_{\max}} \quad (2.10)$$

where $U_{\max}$ is the stored elastic energy at peak stress. The value of η usually depends on the timescale or frequency of cycling.

Other measures of damping include the *specific damping capacity*, $D = \Delta U/U$, the *log decrement*, Δ (the log of the ratio of successive amplitudes of natural vibrations), the *phase-lag*, δ , between stress and strain, and the “*Q*”-factor or *resonance factor*, Q . When damping is small ($\eta < 0.01$), these measures are related by

$$\eta = \frac{D}{2\pi} = \frac{\Delta}{\pi} = \tan \delta = \frac{1}{Q} \quad (2.11)$$

but when damping is large, they are no longer equivalent.

USING LOSS COEFFICIENTS

A bell with a natural frequency of $f = 1000\text{Hz}$ is made of a material with a loss coefficient $\eta = 0.01$. For how long will it ring after being struck? If the material is replaced by one of lower damping with $\eta = 10^{-4}$, how long will it ring? (Assume the ring has ended when the amplitude of oscillation A has fallen to one hundredth of its initial value.)

Answer

Let A and $A + dA$ be amplitudes of successive cycles (dA is negative). Then

$$\text{Log} \left(\frac{A}{A + dA} \right) = \Delta = \pi\eta \text{ from which } \frac{dA}{A} = \frac{1}{10^{\pi\eta}} - 1$$

Integrating over n cycles gives $\ln \frac{A}{A_0} = \left(\frac{1}{10^{\pi\eta}} - 1 \right) n$ where A_0 is the initial amplitude. When A has fallen to $0.01A_0$, the term $\ln(A/A_0) = -4.6$, giving $n = 4.6 \left(\frac{10^{\pi\eta}}{10^{\pi\eta} - 1} \right)$. Thus a bell with $\eta = 0.01$ will ring for $n = 66$ cycles, giving a time $n/f = 66$ milliseconds. A bell with $\eta = 10^{-4}$ will ring for $n = 6400$ cycles and a time of $n/f = 6.4$ seconds.

Wear rate. Wear, the loss of material when surfaces slide against each other, is a multi-body problem—it depends on both the sliding material, the material on which it is slid, and anything that lies between them. Nevertheless, wear can, to a degree, be quantified. When solids slide the volume of material lost from one surface, per unit distance slid, is called the wear rate, W (units: m^3/m , or m^2). The wear resistance of the surface is characterized by the *Archard wear constant*, K_A (units: $1/\text{MPa}$), defined by the equation

$$\frac{W}{A} = K_A P \quad (2.12)$$

where A is the area of the slider surface and P is the pressure (force per unit area) at the contacting surfaces.